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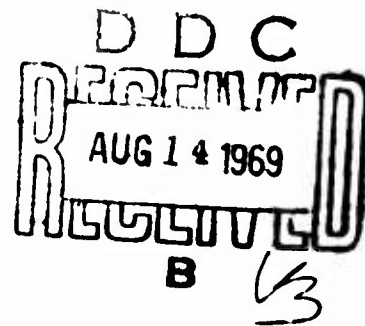USAAMRDL ltr, 23 Jun 1971

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USAAVLABS TECHNICAL REPORT 68-74

A CAPACITIVE MEASUREMENT SYSTEM FOR THE NONDESTRUCTIVE TESTING OF FIBER GLASS REINFORCED PLASTIC LAMINATES

By

Strether Smith

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U. S. ARMY AVIATION MATERIEL LABORATORIES FORT EUSTIS, VIRGINIA

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This program was carried out under Contract DA 44-177-AMC-115(T) with Stanford University.

The report describes the development, theory, and technique for using a capacitative measurement system for nondestructively testing fiber glass reinforced plastic laminates.

The report has been reviewed by the U.S. Army Aviation Materiel Laboratories and is considered to be technically sound. It is published for the exchange of information.

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USAAVLABS Technical Report 68-74
January 1969

A CAPACITIVE MEASUREMENT SYSTEM FOR THE NONDESTRUCTIVE TESTING OF
FIBER GLASS REINFORCED PLASTIC LAMINATES

SUDAAR No. 321

By

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ABSTRACT

The feasibility of utilizing capacitive measurements for the nondestructive testing of epoxy fiber glass composites is discussed. A simple theory is derived from parallel plate capacitor theory and the results are proven by experiment. It is shown that capacitive measurements can be used to accurately determine the thickness and resin glass ratio with an essentially one-sided test.

FOREWORD

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INTRODUCTION

During the past decade, numerous processes for the nondestructive testing of reinforced plastic laminates have been investigated. Emphasis has been placed on ultrasonic and radiographic methods. Some work has been done on thermal and microwave systems. All of these approaches provide some useful information and insight into the makeup of a specimen. None is infallible. Indeed, no combination of presently available test techniques can provide sufficient information to completely describe a specimen.

The investigation, described here, was undertaken to assess the applicability of capacitive measurements. This principle has been neglected previously because of the apparent complexity and cost involved. In this report, a very simple, inexpensive device is described and a straightforward theory derived. Correlation is shown between capacitive measurements, the geometric properties and resin content of a group of fiber glass epoxy panels.

IDEAL CAPACITOR THEORY

Simple, parallel plate capacitor theory gives the formula

$$C = \frac{K}{(d-t) + (t/\epsilon_c)}$$

where

       C = Capacitance
       K = Constant determined by plate geometry and units used
       d = Distance between capacitor plates
       t = Thickness of dielectric
       ϵ_c = Specimen dielectric constant

for the geometry shown in Figure 1.

If we define $K\Delta C'_o$ as the change in capacitance arising from a change in $(d-t)$ from infinity to zero (the plates are brought into contact with the specimen from infinite separation).

$$K\Delta C'_o = C_{(d-t)=o} - C_{(d-t)=\infty} = K/t/_{\epsilon_c} - K/\infty \qquad (1)$$

$$\Delta C'_o = \epsilon_c/t$$
$$\epsilon_c = \Delta C'_o t \qquad (2)$$

Then, if $K\Delta C'_D$ represents the change in capacitance arising from a change in $(d-t)$ from ∞ to any quantity greater than zero,

$$K\Delta C'_D = \frac{K}{(d-t) + t/\epsilon_c} - \frac{K}{\infty} = K/(d-t) + 1/\Delta C'_o \qquad (3)$$

$$\Delta C'_D = \frac{\Delta C_o}{\Delta C'_o (d-t) + 1}$$

and

$$(d-t) = \frac{1}{\Delta C'_D} - \frac{1}{\Delta C'_o}$$

thus,
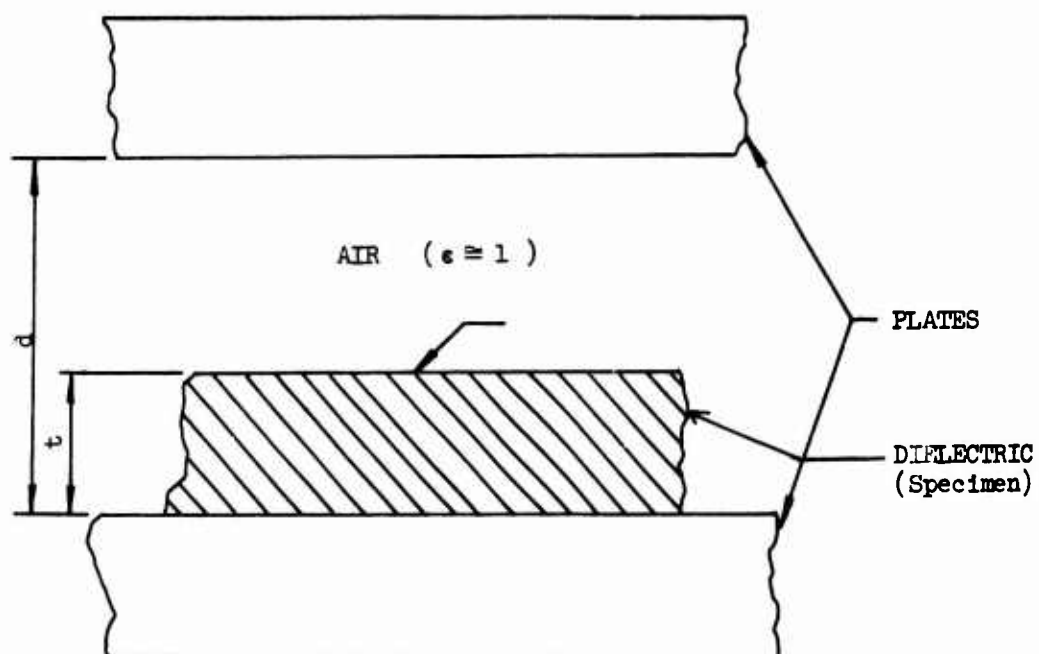
Figure 1.   The Ideal Parallel Plate Capacitor

$$t = d - \frac{1}{\Delta C'_D} - \frac{1}{\Delta C'_o} = \text{"Capacitive Thickness"} \qquad (4)$$

$$= \tau$$

Now, "d" is an easily measurable quantity, and, if we can measure $\Delta C'_D$ and $\Delta C'_o$, we can define the "capacitive thickness" (which is equal to the true thickness for the ideal specimen) from Equation (4). Then, the capacitive thickness" may be entered into Equation (2) to determine the dielectric constant.

CORRELATION PARAMETERS

The theory derived above develops relationships between capacitive measurements and the two parameters: "capacitive thickness" and indicated dielectric constant. The thickness is of direct value to the structural plastics engineer. The dielectric constant is not. However, the latter property can be linked to meaningful parameters, as will be shown.

The specimen considered is a two-component composite, a glass epoxy system. The measurements will be sensitive to the dielectric constants of the two materials, and this parameter is listed below for a number of commonly used components.

Materials	Dielectric Constant
"E" Glass	5.90
"S" Glass	4.57
Epoxy Resins	3.0 - 3.8

Fortunately, as may be seen above, glass and epoxy have widely different dielectric constants. Thus, we may separate the effects of the two materials.

The dielectric constant of a composite can be regarded as the appropriately weighted average of the dielectric constants of its constituents. Thus,

$$\epsilon_c = \frac{t_R \epsilon_R + t_g \epsilon_g}{t_c} \tag{5}$$

t_R = Thickness of resin

t_g = Thickness of glass

t_c = Thickness of composite = total thickness

ϵ_R = Dielectric constant of resin system

ϵ_g = Dielectric constant of glass

ϵ_c = Dielectric constant of composite

This equation is based on the assumption that the composite is made up of alternate layers of resin and glass.

Now, ϵ_c is the measured dielectric constant derived earlier. Equating expressions 2 and 5, and multiplying through by the thickness, we get

$$\Delta C_o' t_c^2 = t_R \epsilon_R + t_g \epsilon_g \tag{6}$$

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Substituting the capacitive thickness for t_c, we have

$$\Delta C_o' \tau_c^2 = t_R \epsilon_R + t_g \epsilon_g \qquad (7)$$

where

$$\tau = d - \frac{1}{\Delta C_D'} - \frac{1}{\Delta C_o'}$$

In the series of tests described in this report, the amount of glass per unit area is assumed to be a constant and the dielectric constants, ϵ_R and ϵ_g, are taken as constant. Therefore,

$$t_g \epsilon_g = K \qquad (8)$$

and

$$\Delta C_o \tau^2 = \epsilon_R t_R + K \qquad (9)$$

Since the resin density is, to all intents and purposes, invariant, we may assume that t_R is proportional to the resin weight per unit area.

Thus,

$$\Delta C_o' \tau^2 = K_1 (\text{weight/unit area}) + K \qquad (10)$$

The weight per unit area and $\Delta C_o' \tau^2$ are one set of parameters used in the correlation, and they are linearly related for specimens of the type used in this study.

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THE CAPACITIVE COMPARATOR

The electrical circuit used in the probe has been described by earlier investigators (Ref. 1). It is shown with the appropriate electrical parameters in Figure 2. The probe, itself, is very similar to those used as deflection transducers (Ref. 2). It has sensitivity as a gap measuring device of about 20 volt/inch at a gap of 0.050 inch. The output voltage of the device is d.c. and is easily measured with a high impedance voltmeter.

Since capacitance, as such, is not of direct concern and we wish to calibrate out nonidealities, the voltage output at the probe is a convenient parameter. Thus, ΔC_o and ΔC_D, used in the correlations are proportional to $\Delta C_o'$ and $\Delta C_D'$, used in the derivation, provided the electronics give a voltage output that is linear with capacitance.

Over a small range, the voltage output of this circuit is linear with capacitance. However, if the change in capacitance is greater than 10 percent of the initial value, nonlinearities too large to ignore may occur.

The geometry of the probe and mounting system is shown in Figures 3 and 4. It may be seen that the probe capacitor face is quite small and that it is looking at a large flat plate. Thus, fringing will occur, and this may cause difficulty in some applications.

The two deviations from ideality require that we investigate the consequences which might occur. The nonlinearity arising from the electronics can be checked by testing a series of specimens with widely varying thicknesses and comparing the actual and capacitive thickness. The results of tests of this type are given in Figure 5, and it is seen that the correlations show good linearity.

Thus, we may assume that this effect is not important for our tests.

However, the fringing problem does lead to difficulties. If specimens of different dielectric constants are checked for capacitive thickness, there is a change in indication with specimen material for a given thickness. Results of a test of this type are shown in Figure 6. It may be seen that varying the dielectric constant by a factor of two results in a capacitive thickness error of about 12 percent. Thus, fringing introduces some cross coupling between the thickness and dielectric constant determination. Fortunately, for testing of a series of fiber glass-epoxy specimens, the change in dielectric constant is not large enough to cause great difficulty, despite wide resin-glass ratio variations.

---

[1] Foldvari, Tibor L., and Lion, Kurt, S; CAPACITIVE TRANSDUCERS, Instruments and Control Systems, Nov. 1964, pp. 77 to 85

[2] Smith, Strether, and Craig, James I; CAPACITIVE INSTRUMENTATION FOR STRUCTURES RESEARCH, in preparation.
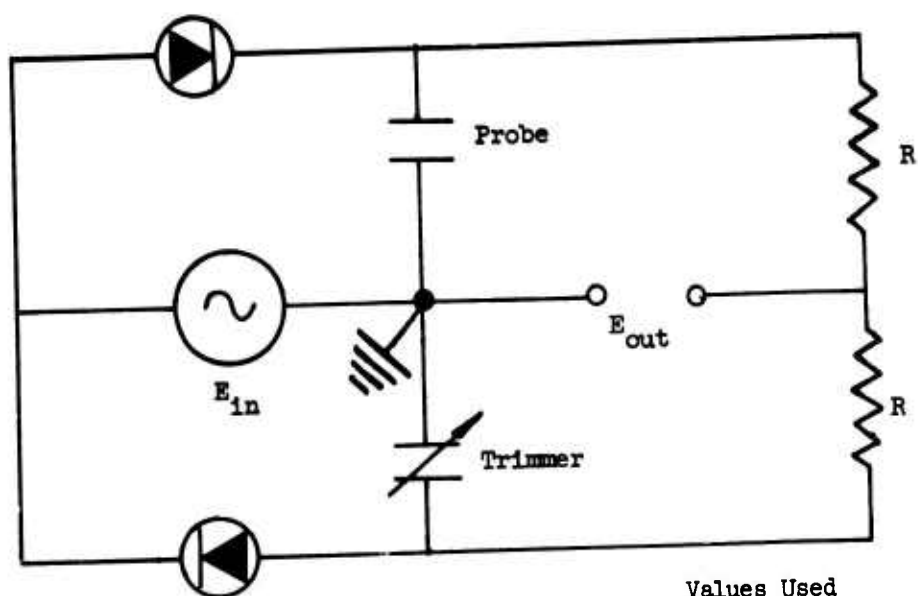
Values Used
E_{in} = 100 KHZ. 24v RMS
E_{out} = Read With VTVM
R = 1 Megohm
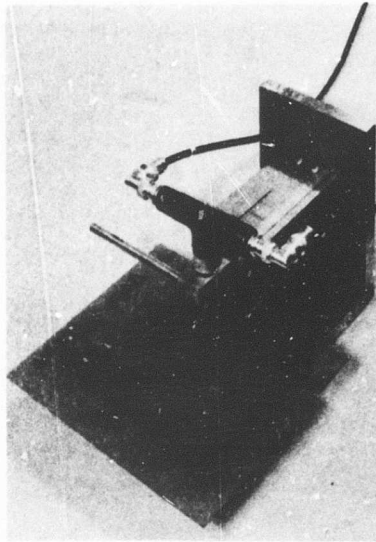
Figure 2. "Twin-T" Network
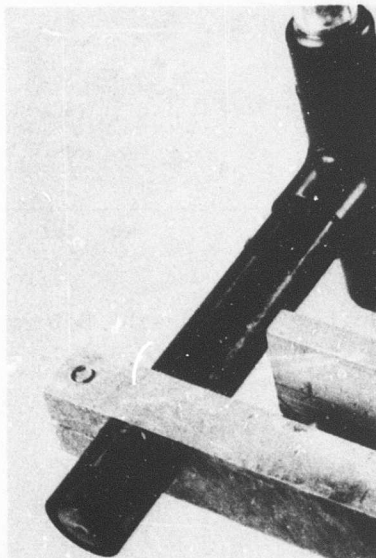
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Figure 3. The Capacitive Comparator

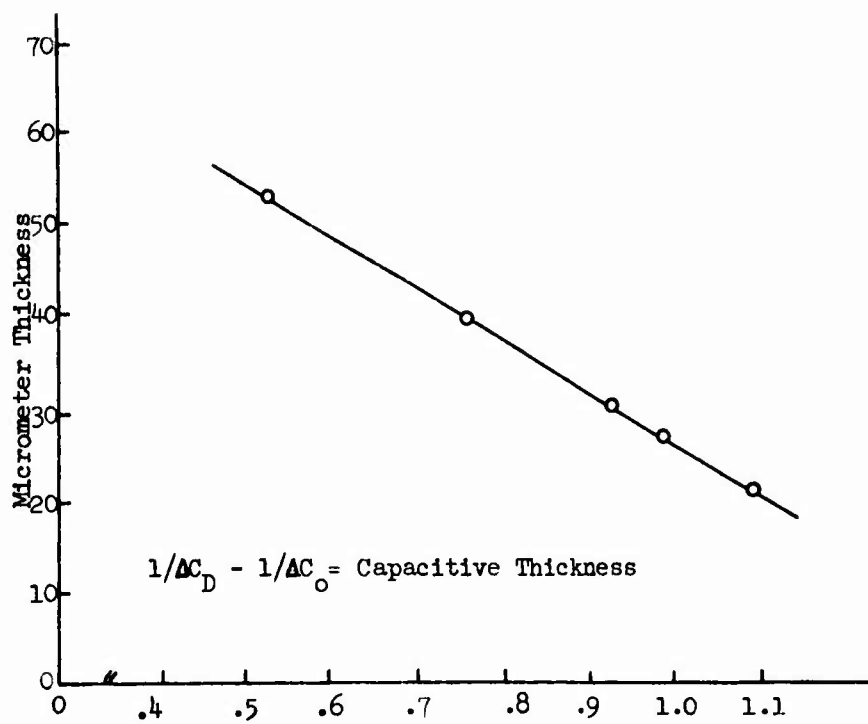Figure 4. Capacitive Probe Tip

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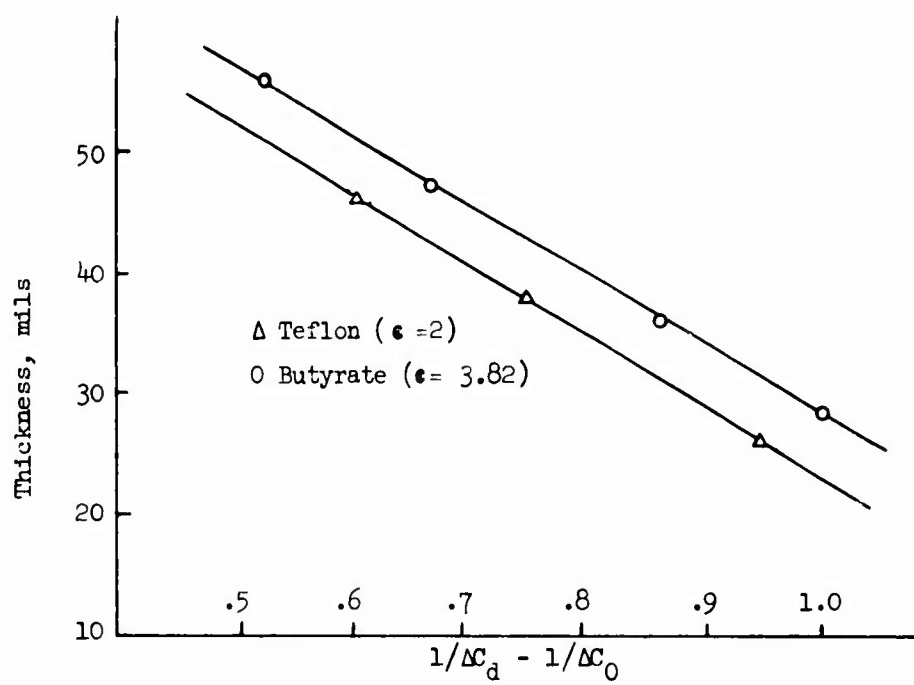Figure 5. "Capacitive Thickness" Determination for Lexan Polycarbonate Plastic.

Figure 6.   The Effect of Variations in Dielectric Constant
            on the Measurement of Capacitive Thickness.

TEST PROCEDURE

A drawing of the "two-sided" test device is shown in Figure 7. The rig provides a stable reference for the probe and an adjustable stop to fix "d".

The test procedure is as follows:

1. The probe is removed from the rig and the voltage is measured. This corresponds to the capacitance at $d-t = \infty$.

2. The rig is reassembled, and the stop is set such that the gap "d" is about twice the maximum specimen thickness anticipated.

3. Two test specimens which represent the maximum and minimum thicknesses anticipated are inserted. Voltage readings are taken with the probe touching the specimen and with it against the stop. These readings, when the "$d-t = \infty$" reading is subtracted, correspond to ΔC_o and ΔC_D. The "capacitive" thickness is calculated from the equations given, and the values from the two specimens are plotted against micrometer thickness. A straight line is drawn between the two points, and the device is now calibrated for thickness.

4. The procedure is repeated for two specimens which represent the limits of weight per unit area expected. τ, the capacitive thickness, is determined, and this quantity squared is multiplied by ΔC_o. This gives $\Delta C_o \tau^2$ for each specimen, which is correlated against measured weight/unit area; a straight line is drawn between the two points. The device is now calibrated to determine panel weight per unit area.

In steps 3 and 4, it is important that the reference samples have about the same dielectric constant and thickness as the specimens to be tested. Otherwise, errors from the nonidealities discussed previously may arise.

5. The specimens (structures) under scrutiny may now be tested to obtain ΔC_o and ΔC_D as in the calibration procedure. The calculations are then made, and the capacitive thickness and weight/unit area are obtained from the appropriate calibration chart.
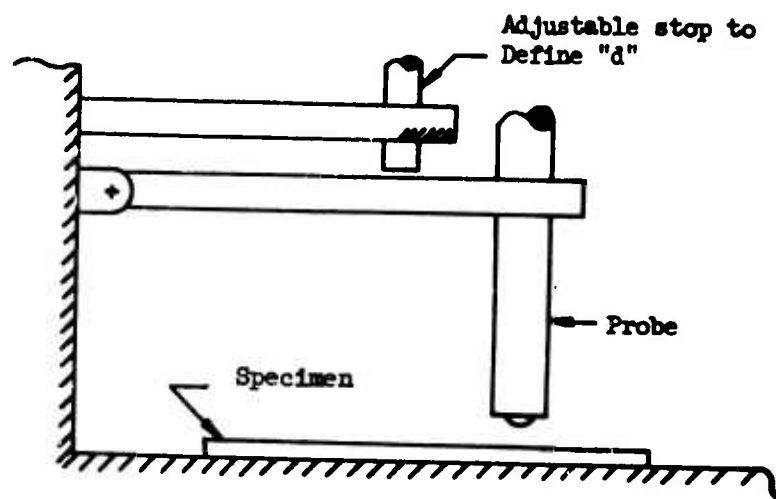
Figure 7. The Two-sided Test Device.

RESULTS

Results from tests on a series of fiber glass-epoxy panels are shown in Figures 8 and 9. The panels were manufactured from four sheets of 2P-181-Volan A glass cloth impregnated with Epon 826-Methane Diamine epoxy resin. They were made with varying resin contents at different laminating pressures. This resulted in widely varying thicknesses and different resin-glass ratios from panel to panel.

"Capacitive thickness" $\frac{1}{\Delta C_D} - \frac{1}{\Delta C_o}$ is plotted against micrometer thickness in Figure 8. It may be seen that correlation is very good, with few stray points. The worst error from the mean line is .002 inch, or 5 percent.

In Figure 9, the panel weight per unit area is plotted against the product of the indicated dielectric constant and the capacitive thickness. It is seen that, once again, excellent correlation is achieved.

There are a number of irregularities which may occur in the panels that have not been accounted for in the theory. Probably, the most important are the presence of voids and/or porosity and imperfect surface finish. These deviations should make the micrometer thickness greater than that indicated by the capacitive theory. The test presented then provides a conservative lower bound for thickness.

Other errors may result from changes in dielectric constant. It can be seen that the indicated dielectric constants vary about 30 percent from panel to panel. From the earlier test performed to determine the effects of such variations in dielectric constant, we would anticipate a resulting error of about 3 percent. However, this problem is reduced somewhat by adopting a calibration procedure using real panels.

These effects cannot be separated by the technique presented, but the low rate of error found in these test results shows that they can be neglected in most cases.

It should be noted that this is a one-sided test if the specimen can be backed up by an electrically grounded conductor. Thus, this device could be used to determine the thickness and dielectric properties of a filament-wound specimen made on a conductive mandrel.

As a check on the device's capability to determine secondary variations in an epoxy-fiber glass specimen, a series of tests was performed to establish its sensitivity to high-order effects. A series of epoxy castings was produced with the same chemical composition and machined to .061 inch ± .0003 inch thickness. They were cured for varying time intervals; the indicated dielectric constant is plotted against cure duration in Figure 10. The scatter is quite high when compared to the range encountered, but definite trends may be established and, in the cure time region normally associated with this resin system (4 hours), the characteristic curve is quite steep.
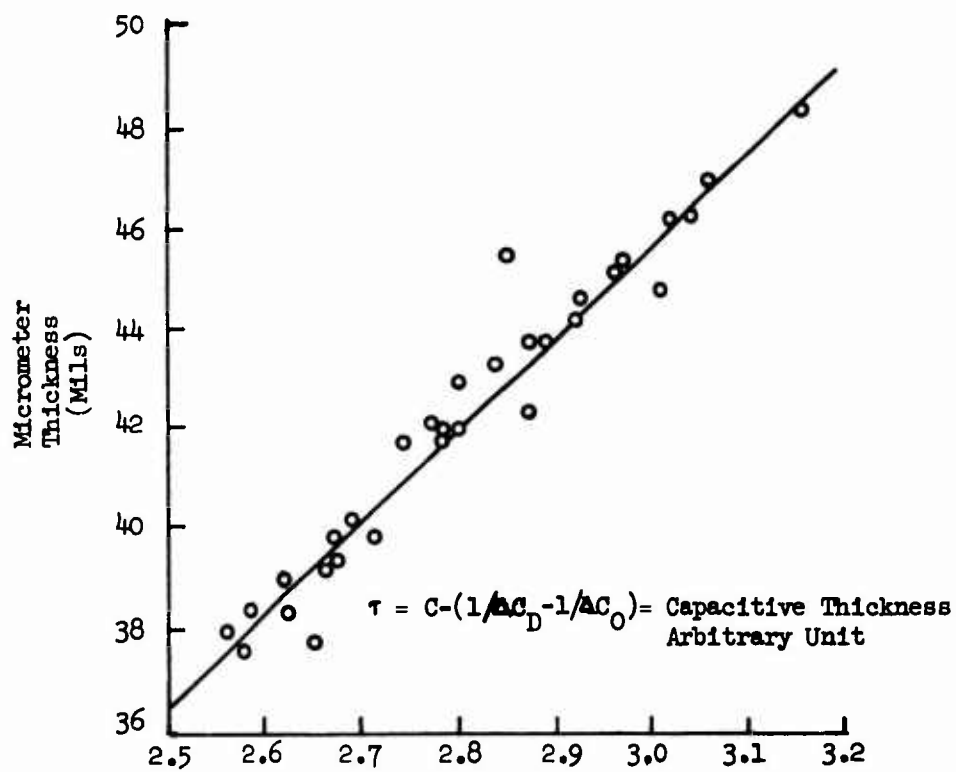
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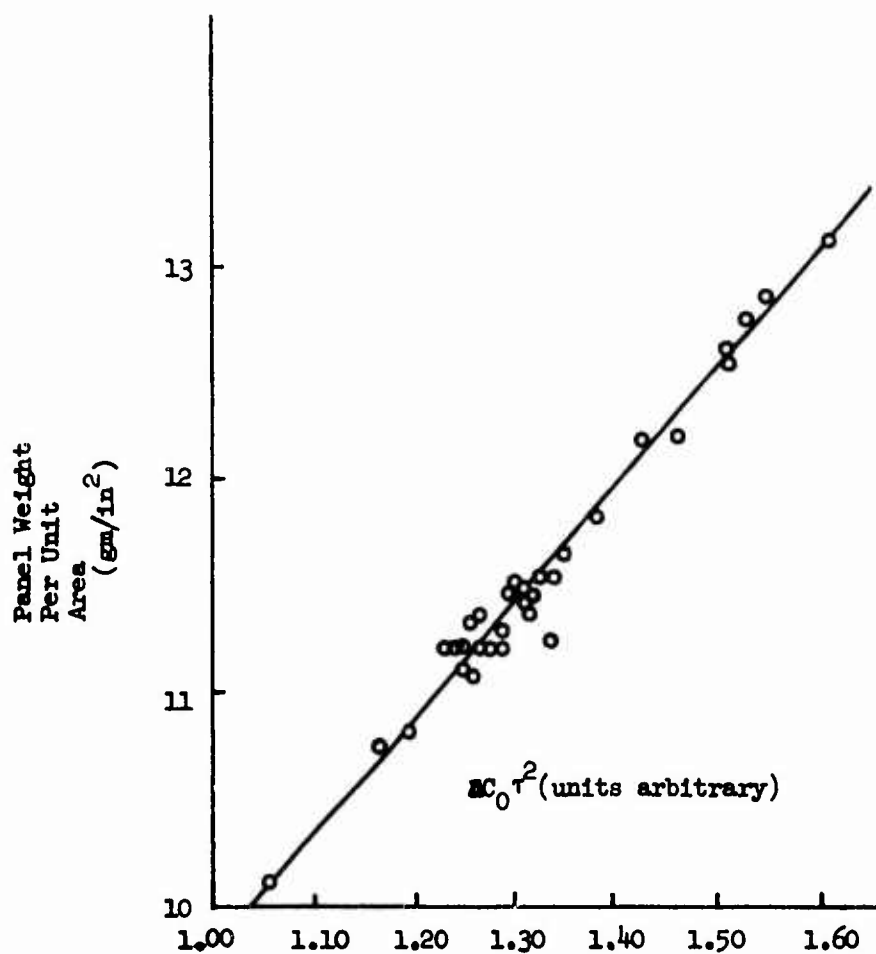Figure 8. Micrometer Thickness Vs. Capacitive Thickness.

Figure 9. Weight Per Unit Area Vs. Indicated
Dielectric Constant X Thickness
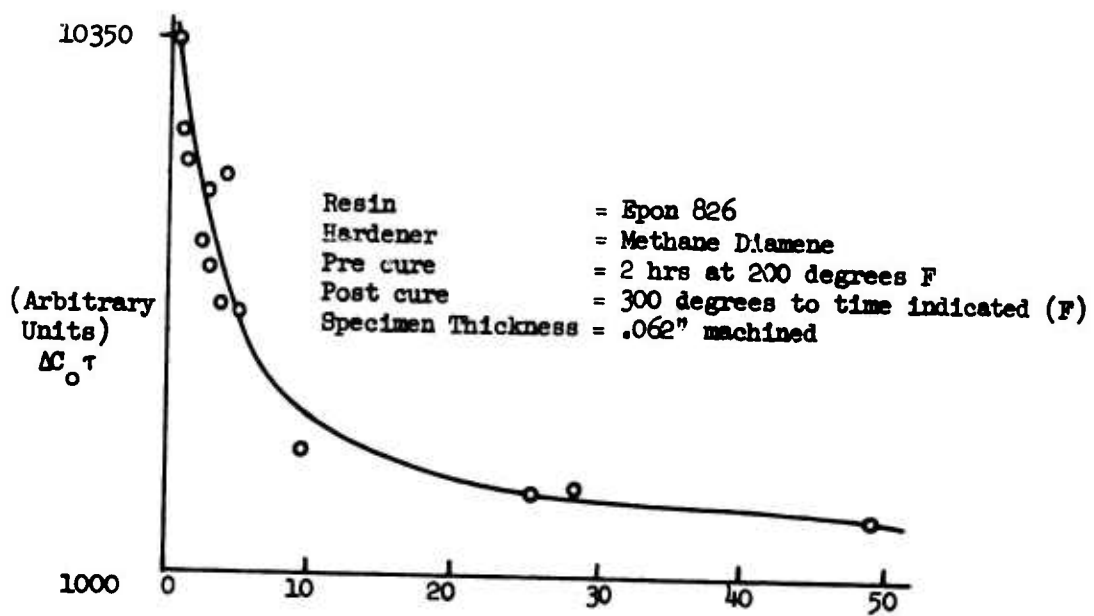
Figure 10. Post-Cure Time Vs. Indicated Dielectric
Constant.

It is expected that, for carefully manufactured castings of this type, the extent of cure could be ascertained to fair accuracy.

Attention should be drawn to the units used for the indicated dielectric constant. It is seen that the range encountered is only 350 parts in 10,000, or 3.5 percent. This variation would be lost in the scatter that occurs in the layup tests. Thus, it appears that, for this resin-glass system, differences in cure could not be detected unless much better control of other secondary effects (voids and surface finish) can be achieved.

A SINGLE-SIDED TEST

A series of experiments was performed to determine whether a purely one-sided device could provide useable results. In these tests, the probe was brought into contact with the surface of panels that did not have one side grounded. The geometry of the situation and the consequent electric field are shown in Figure 11.

Probe output is plotted against panel thickness in Figure 12. It should be noted that this reading will include the effects of variations in both thickness and dielectric constant. Therefore, this technique should probably be used only in a comparative sense.

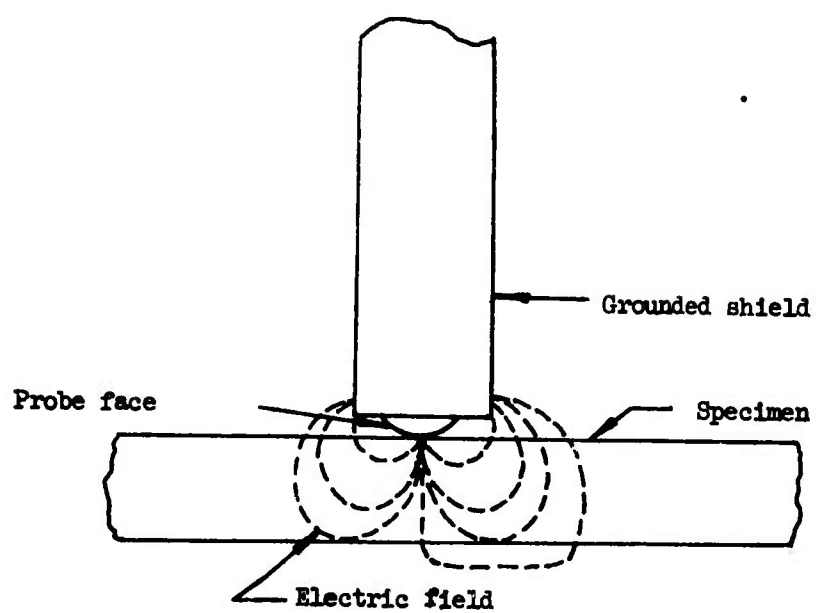This technique does provide a very simple test and can probably be applied in a go no-go system.

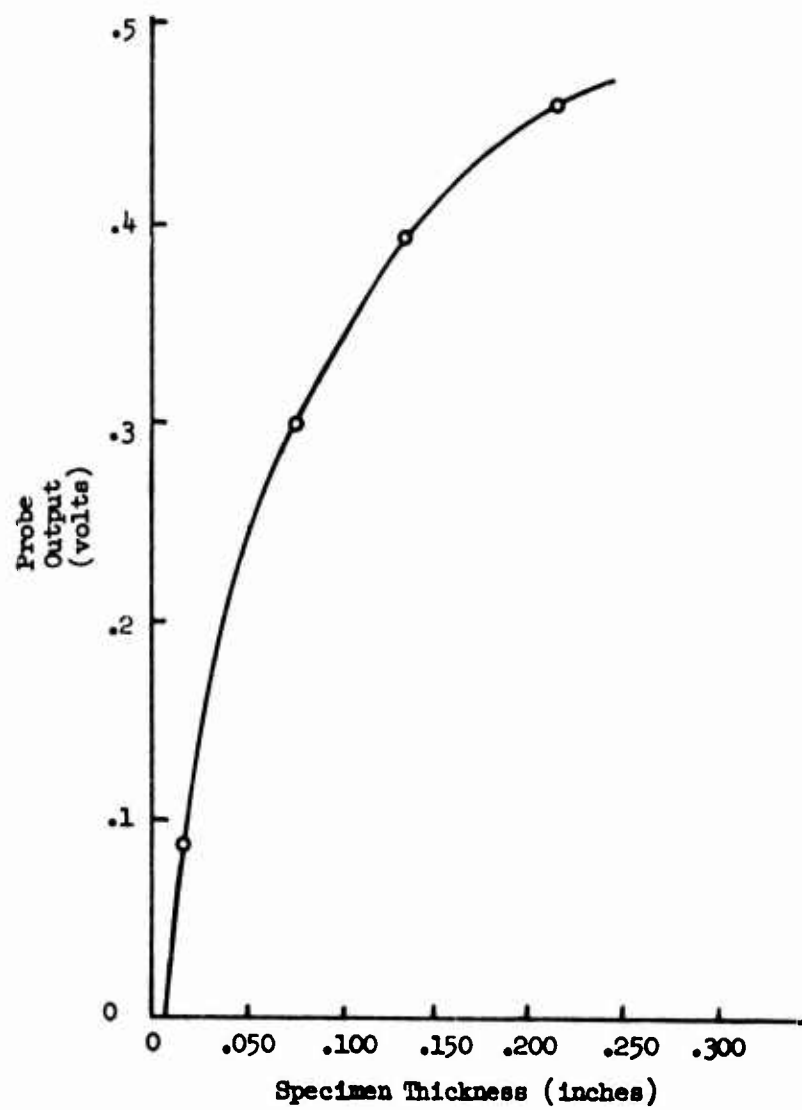Figure 11. Geometry and Electric Field
of One-sided Test.

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Figure 12. Determination of Laminate Thickness by One-sided Test.

CONCLUSION

It has been shown that simple capacitive measurements can provide worthwhile information about the properties of a fiber glass-epoxy composite. For the correlation procedures used and the tests performed in this study, accuracy of better than $\pm$ 5 percent was obtained on both thickness and weight per unit area determinations.

Although this method appears to show great promise for the determination of the thickness and resin content, it is not very sensitive to voids and surface phenomena. It will not detect cracks and delaminations. Thus, the device is not a cure-all.

However, among the nondestructive testing techniques, it is one of the most sensitive tests to determine the thickness and resin content, and the test can be performed essentially from one side.

A secondary advantage of the system is low initial and operating cost. The probe is very simple, both mechanically and electrically, and the test procedure is completely straightforward.

For some applications, parameters other than those derived may be more appropriate. For example, in a filament-wound structure, the resin-glass ratio may be determined if the dielectric constants of the constituents are know. The relationship will be nonlinear and somewhat more difficult to apply than the weight/unit area parameter used in this paper, but no particular difficulty should arise. Derivation of the relationships is straightforward from the theory presented here, although assumptions made should be checked by experiment. It is quite remarkable that calculations based on simple parallel plate theory can predict the performance of very nonideal systems so well.

Thus, another set of parameters has been added to the list of nondestructive test variables available to the plastics engineer. However, the infallible test, or series of tests, is yet to be determined.

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